650V Silicon Carbide Integrated Power Module for Automotive Inverters

Monty B. Hayes

June 20, 2018

Delphi Technologies

Wolfspeed A CREE COMPANY

Oak Ridge National Laboratory

Project ID: elt083

Project Overview

Timeline

Project Start Date: January 1, 2016
Project End Date: February 28, 2018
Percent Complete: 100%

Goals/Barriers

	2020	2025
Cost ($/kW)	<3.3	<2.7
Specific Power (kW/kg)	>14.1	
Power Density (kW/L)	>13.4	>100

WBG device power and voltage levels and availability
WBG multi-physics integration designs to enable optimal use
High temperature and isolation materials

Budget

Total Project Funding:	$2,161,561
DOE Share:	$1,488,303
Contractor Share:	$673,258
Funding Received in 2016:	$656,921
Funding for FY 2017:	$831,381

Partners

Delphi - Lead
Wolfspeed
Oak Ridge National Labs
Volvo

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Relevance Project Objectives

Overall Objectives

- Develop a double-sided cooled 650V Silicon Carbide (SiC) Metal Oxide Semiconductor Field Effect Transistor (MOSFET) packaged power device
    - Capable of traction drive inverter application targeted to meet DOE's 2020 electric drive vehicle (EDV) inverter targets

Objectives This Period

- Complete 650V SiC MOSFET characterization
- Test inverter developed with 650V SiC MOSFET packaged component
- Develop and characterize 1200V SiC MOSFET packaged component (separately funded)
- Test inverter developed with 1200V SiC MOSFET packaged device (separately funded)

Impact

- Addresses the gap of WBG device power and voltage levels and availability

Double-side cooled 650V & 1200V SiC MOSFET Packaged Power Device

Milestones

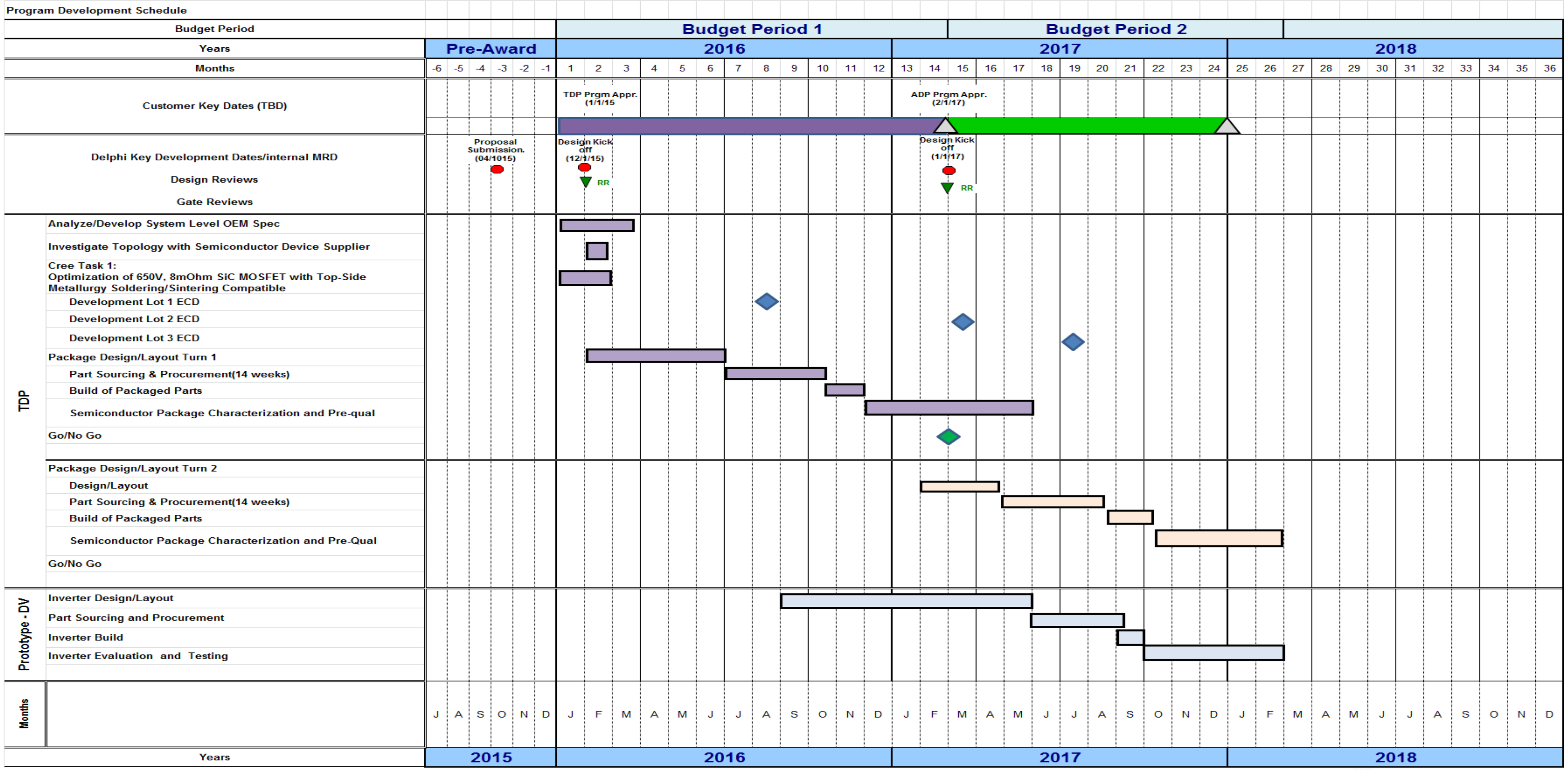
Budget Period 1

Milestone	Type	Description	Status
Configuration Selection	Technical	Selection of 650V SiC MOSFET power semiconductor device/module with an Rdson of 7-8 mΩ. The down selection will include device rated breakdown voltage, current rating and switching frequency for the inverter application.	Complete
Fabrication Completed	Technical	SiC MOSFET device fabrication completed	Complete
Device Build Completed	Technical	SiC MOSFET packaged devices build completed	Complete
Traction Drive Inverter System Design Completed	Technical	Complete design of Traction Drive Inverter System	Complete
Characterization Completed	Go/No-Go	SiC MOSFET packaged devices characterized across temperature and design of inverter. Provide characterization data for the 7-8 mΩ device and projected inverter performance comparison to the DOE 2020 goals. The potential to meet cost and performance goals are assessed to determine if the project should proceed.	Complete

Budget Period 2

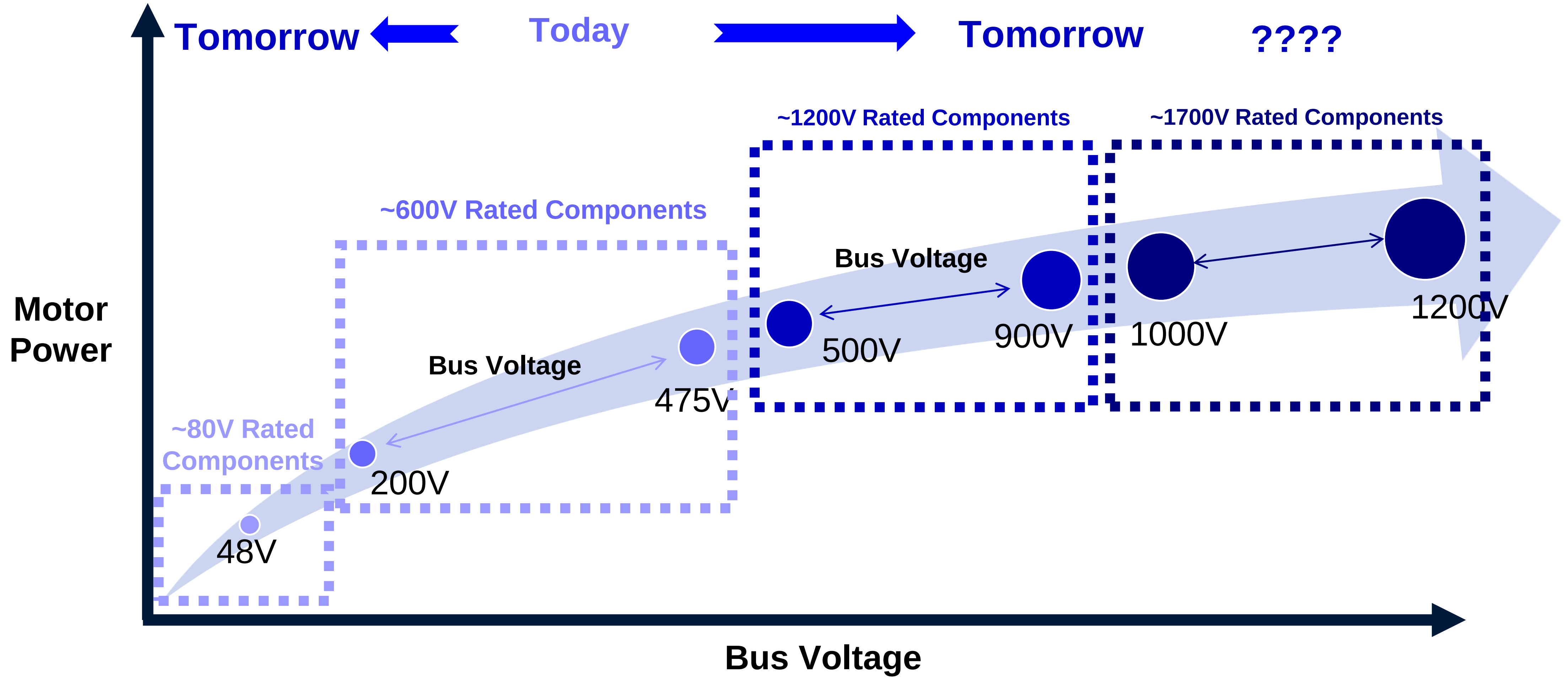
Milestone	Type	Description	
Characterization and Pre-Qualification Completed	Technical	Characterization of SiC MOSFET device completed	Complete
Prototype Design Completed	Technical	Prototype inverter design/layout completed	Complete
Traction Inverter Build and Evaluation Completed	Technical	Build and evaluation of the traction drive inverter completed	Complete
Prototype Test Completed	Technical	Prototype inverter hardware build, debug and test completed	Complete
Characterization Completed	Technical	Semiconductor package characterization and evaluation completed	Complete

Approach



Program Development Schedule
Budget Period
Budget Period 1
Budget Period 2
Years
Pre-Award
2016
2017
2018
Months
-6 -5 -4 -3 -2 -1 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36
Customer Key Dates (TBD)
TDP Prgm Appr. (1/1/15
ADP Prgm Appr. (2/1/17)
Delphi Key Development Dates/internal MRD
Design Reviews
Gate Reviews
Proposal Submission. (04/1015)
Design Kick off (12/1/15)
Design Kick off (1/1/17)
RR
RR
TDP
Analyze/Develop System Level OEM Spec
Investigate Topology with Semiconductor Device Supplier
Cree Task 1:
Optimization of 650V, 8mOhm SiC MOSFET with Top-Side Metallurgy Soldering/Sintering Compatible
Development Lot 1 ECD
Development Lot 2 ECD
Development Lot 3 ECD
Package Design/Layout Turn 1
Part Sourcing & Procurement(14 weeks)
Build of Packaged Parts
Semiconductor Package Characterization and Pre-qual
Go/No Go
Package Design/Layout Turn 2
Design/Layout
Part Sourcing & Procurement(14 weeks)
Build of Packaged Parts
Semiconductor Package Characterization and Pre-Qual
Go/No Go
Prototype - DV
Inverter Design/Layout
Part Sourcing and Procurement
Inverter Build
Inverter Evaluation and Testing
Months
J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D
Years
2015
2016
2017
2018

Approach
Electric Propulsion Trends



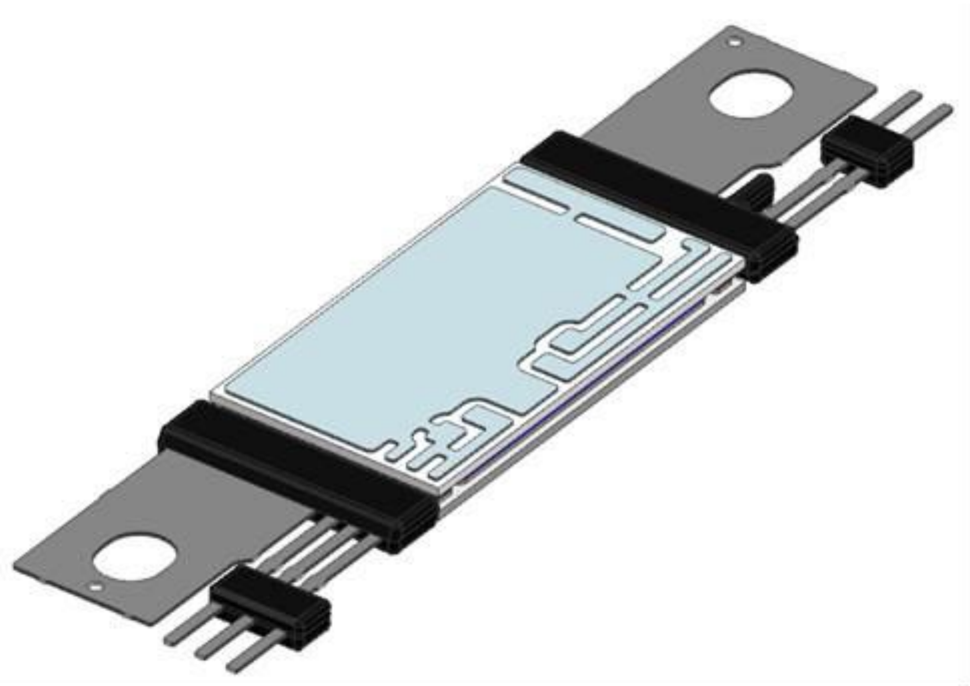
Higher Power for Premium/Performance drives Bus Voltages

Approach
Viper Technology - Scalable

- Scalable Viper Solutions to cover various product needs

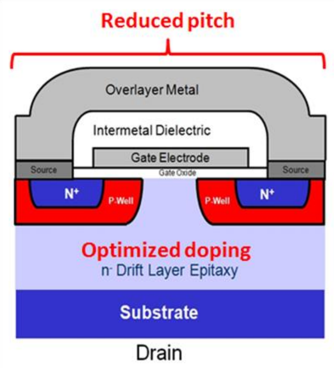
- Can be used with different die sizes and breakdown voltages to meet customer needs

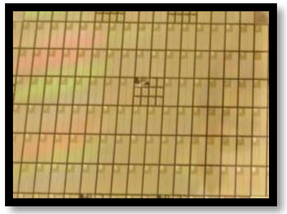
- Can utilize semiconductors from various world class Tier 2s
- Optimized switching and conduction losses
- Optimized for vehicle drive cycle



Technical Accomplishments
650V & 1200V SiC MOSFET Goals
For Traction Inverter Drive Applications

- 650V and 1200V Rated Breakdown Voltage
- Designed to support 300 to 1200Arms inverter phase currents
- Targeting 7-8mΩ R_{DSON} for 650V rated devices, 175°C Junction Temperature rated
- Targeting 10-12mΩ R_{DSON} for 1200V rated devices, 175°C Junction Temperature
- Plated metal stack designed for top-side soldering or sintering
- Eliminates wirebonds
- Allows for Double Side Cooling
- Smaller amount of semiconductor as compared to Si IGBT and Diode to minimize costs
- Optimized for vehicle drive profiles
- Reliability goals to meet automotive requirements



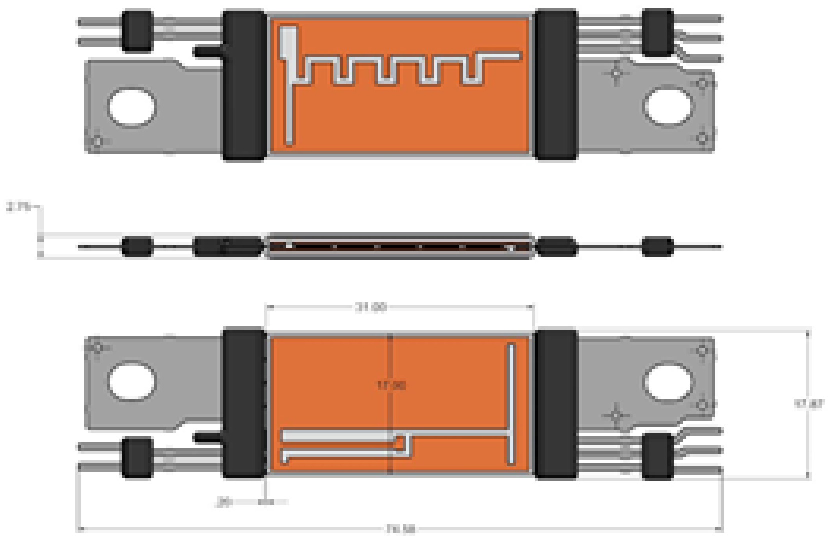


650V, 7-8m mΩ RDSON, 1200V, 10 -12 mΩ RDSON,175°C SiC MOSFET

Technical Accomplishments
Dual-sided Cooled Packaged Device Assembly
Previously Shown

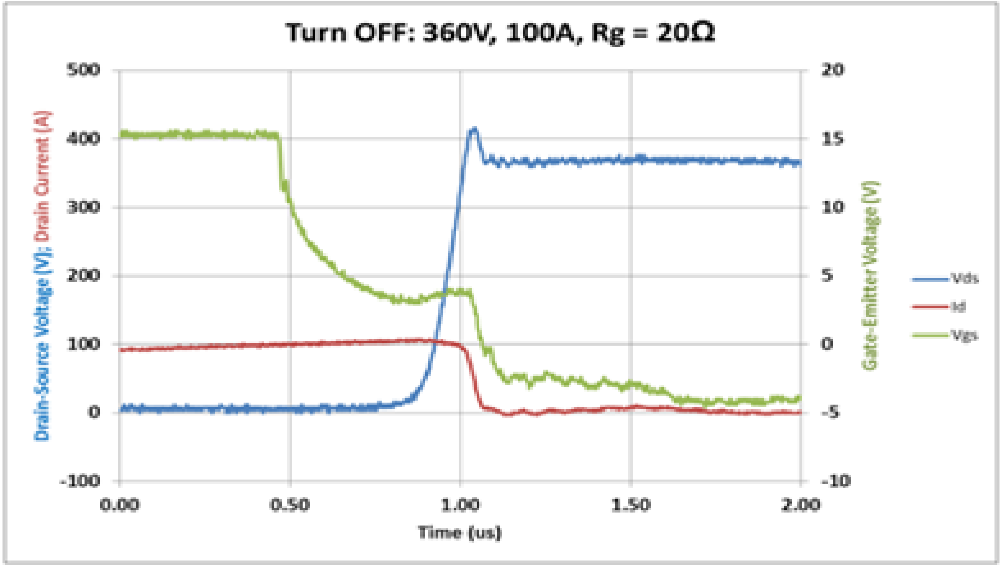
Delphi Packaged Power Device

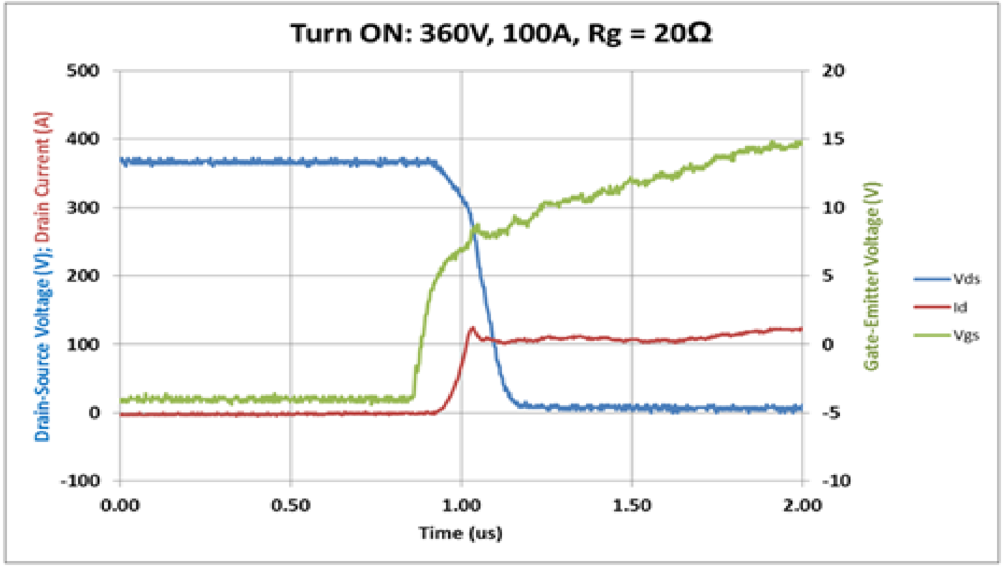
- 650V and 1200V rated packages
- 5 MOSFETs in parallel
- Thermistor
- Pb-free solder or sinterable
- 500Arms capability for 650V rated packages
- 480Arms for 1200V rated packages
- 175°C Junction Temperature (Capable of higher temperatures)



650V and 1200V Rated Semiconductor Package

Technical Accomplishments SiC Die Dynamic Device Characterization





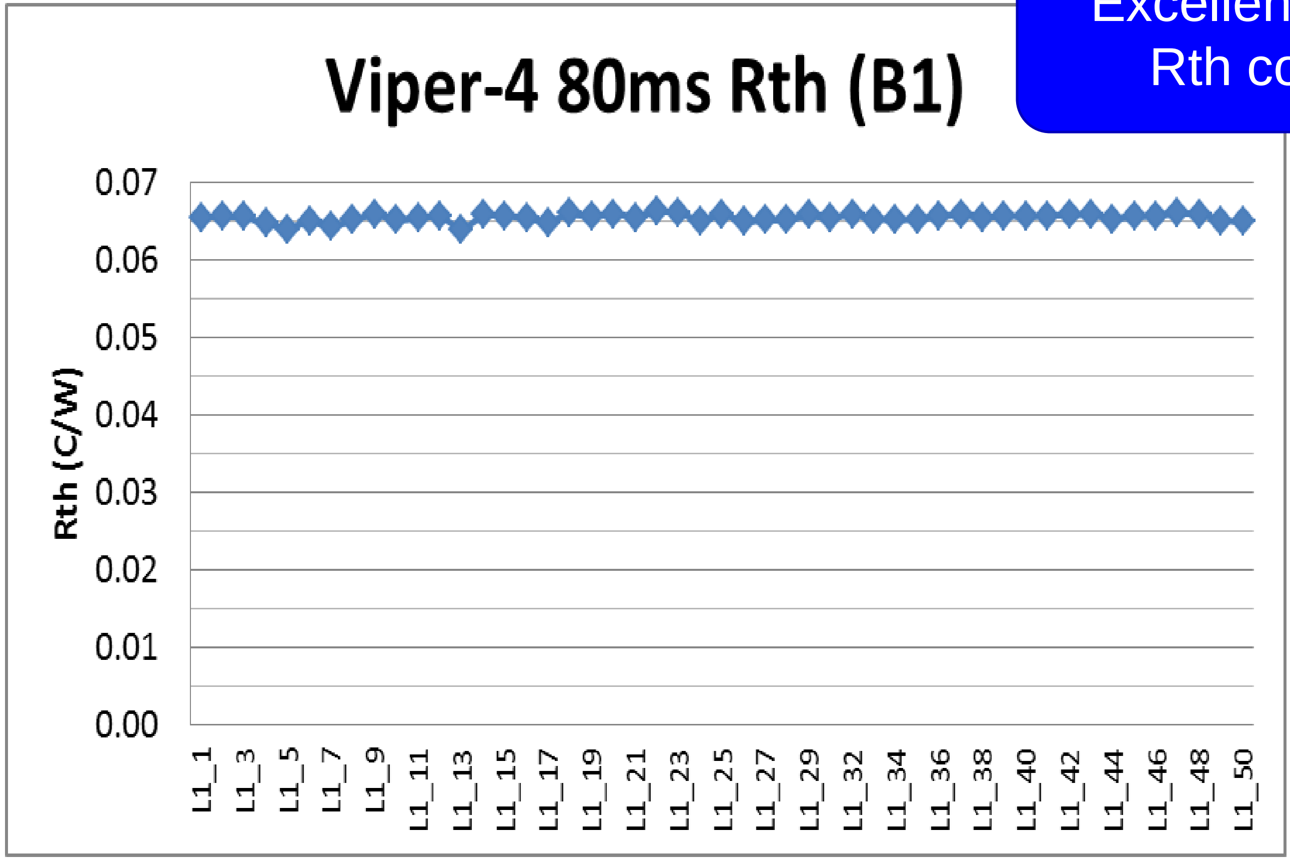
Gate Drive +15/-4V, External R_g = 20Ohm, On Chip R_g Optimized to Reduce Oscillations

Technical Accomplishments
SCM Dynamic Current Sharing Observations

- No dynamic imbalance in current sharing observed in paralleled MOSFETs

Technical Accomplishments
Viper 4 R_{th} (650V) – Thermal Resistance

- Transient Thermal Resistance
  - 80ms
  - 60A
  - ~200W
  - Diode Mode



Excellent part-to-part Rth consistency

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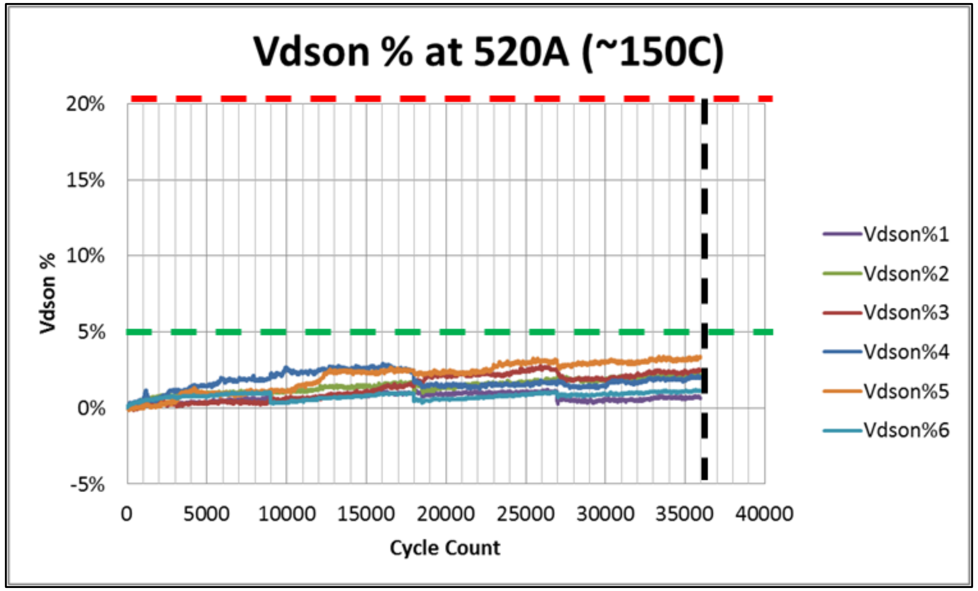
Technical Accomplishments
650V SiC MOSFET Reliability Testing
Power Cycling Data

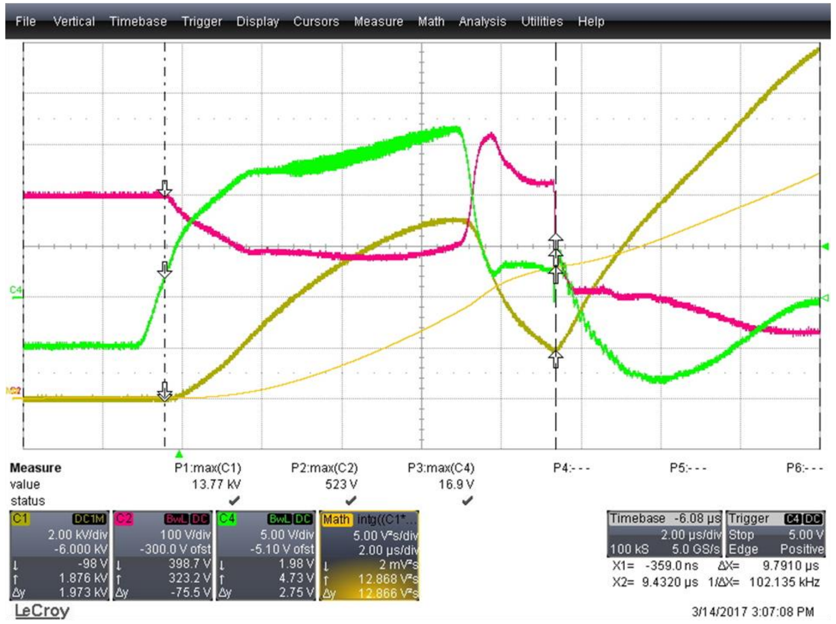
- 5 sec pulses
- Per phase [shoot-through current]
- 10 sec off-time
- 25 sec period [all three phases running]
- 3456 cycles per day [all three phases running]
- 36,000-cycle requirement with endpoint approximately every 9,000 cycles
- ΔT_J of 100˚C
- 50C to 150C target settings
- DC setup currents of 520A, 520A and 520A



Less than 5% Increase in R_{DSON} Over 36,000 Cycles with ΔTJ of 100˚C

Technical Accomplishments
650V SiC MOSFET Reliability Testing
Short Circuit Current

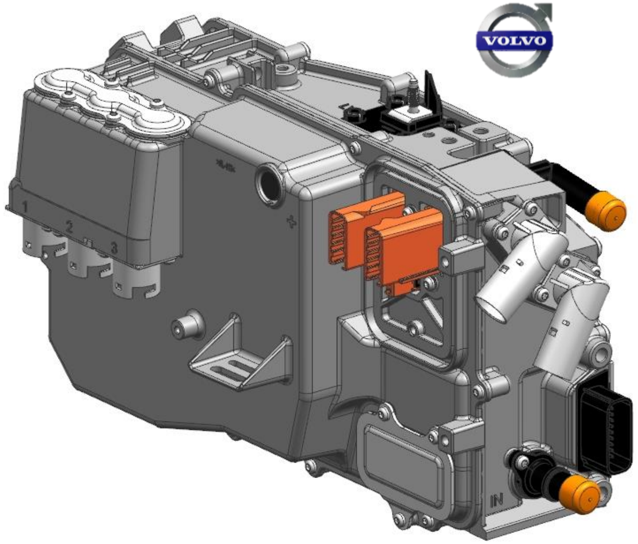
- Target application is for motor drive, short-circuit current rating is also important
- Most commercial SiC MOSFETs typically have short-circuit ratings of 2-3µs in the 650V-1200V rating at this time
- Although preliminary, most of the initial measurements are encouraging with 8µs of short-circuit capability measured before failure



Short Circuit time of 8uS

Integrated Single Inverter/Converter

- Sealed / Chassis mount
- PHEV / BEV Applications
- 3-phase connection designed for pigtails



Electrical Specifications	
Operating Voltage Range:	270 - 400 V
Inverter Peak AC Current:	425Arms (10 sec.)
Inverter Continuous AC Current: rms	185 Arms
Inverter Continuous DC Current:	190 Amps
DC/DC Continuous 14V Current:	160 Amps

Mechanical Specifications	
Dimensions (mm):	336 x 210 x 140
Mass (kg):	<10.5
Mounting Environment:	Chassis / Under-hood
Thermal System: Coolant Coolant Temperature Flow rate	 50% WEG -40 to 65°C Max. 6 L/min Max.
Operating Ambient Temp.:	-40°C to 105°C
High Voltage Connections:	Bolted AC / Pluggable DC

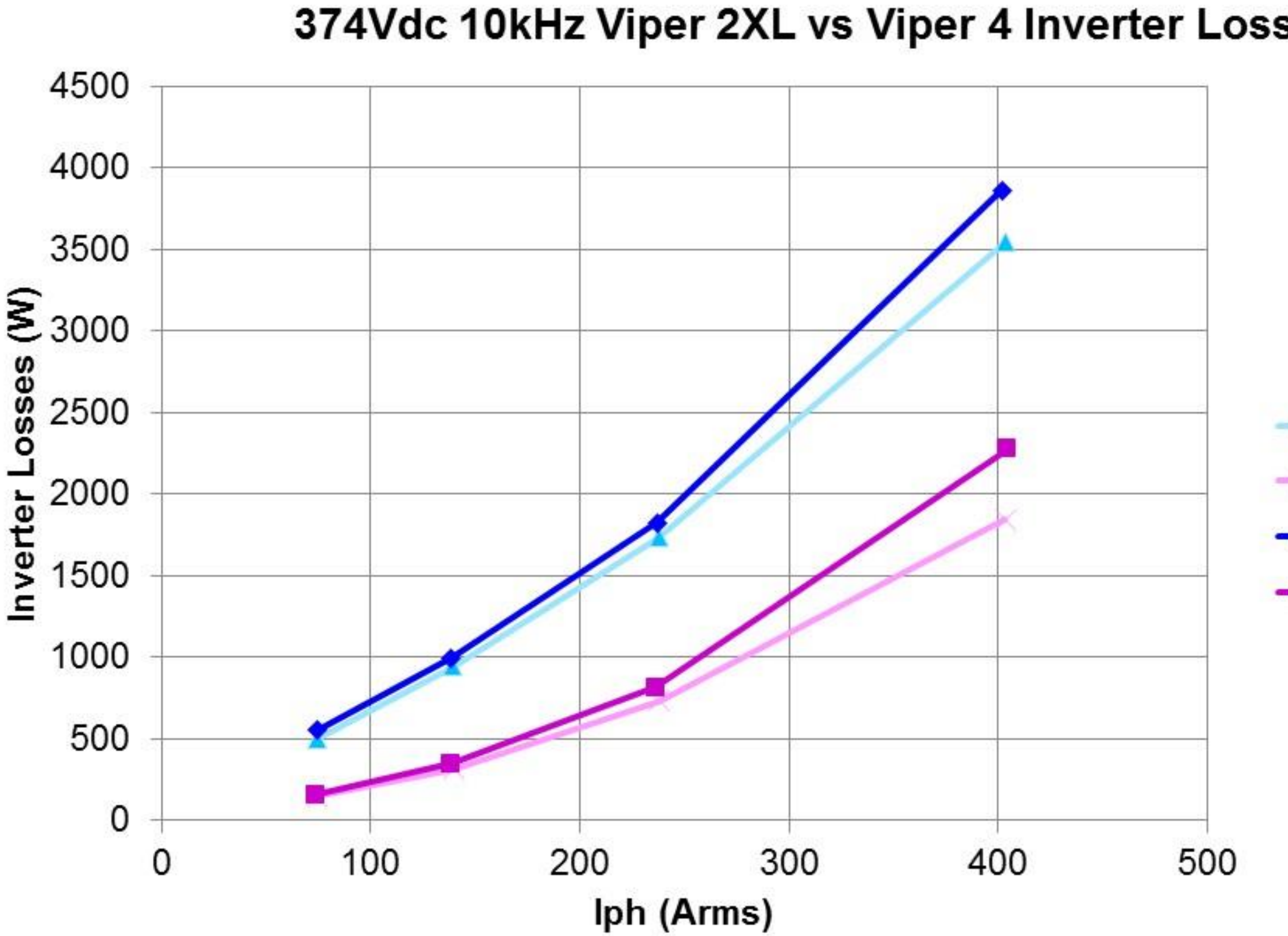
650V SiC vs Si IGBT/Diode Loss Comparison

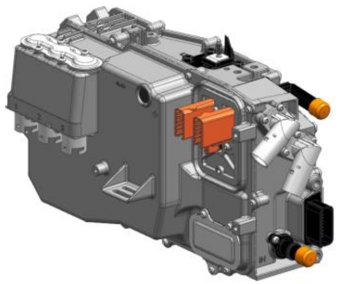
Viper 2: Si IGBT and Diode

- Built in Temperature Sense Diode

Viper 4: SiC MOSFET

- Thermistor on substrate for temperature estimation

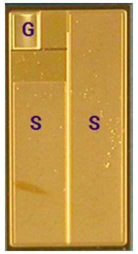




Technical Accomplishments
Future electric propulsion could be more efficient

Silicon carbide high efficiency inverters

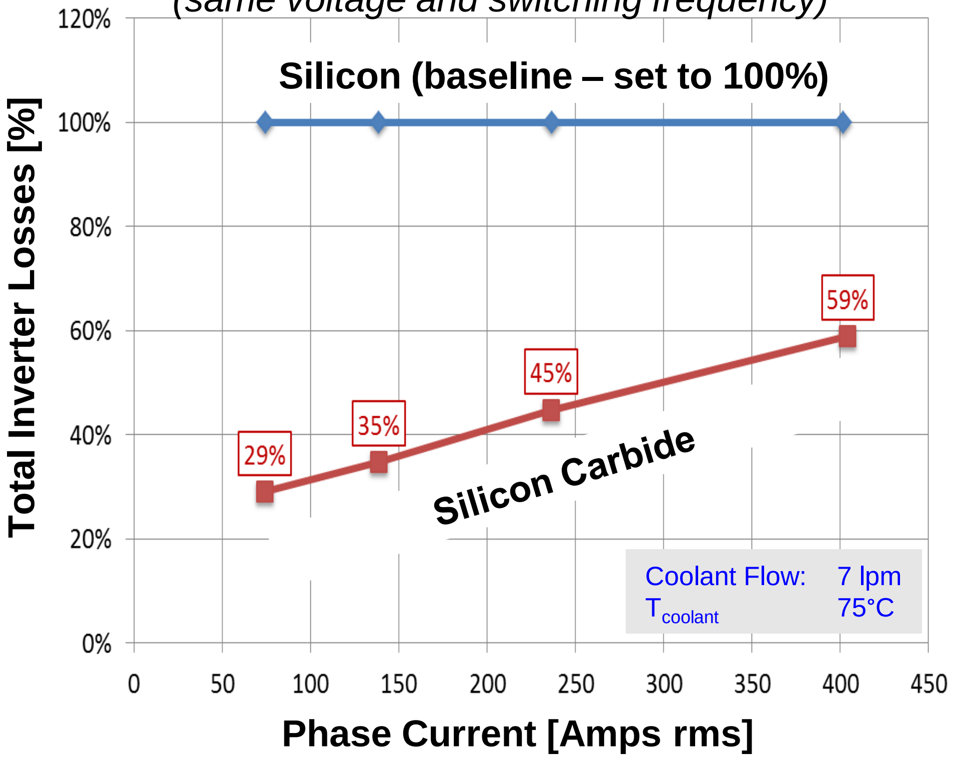
- **"Futureproof" – Viper package used to package SiC MOSFET switches**
- **Lower switching losses than IGBT technology**
- **Inverter level testing shows lower losses**
- **Implication: more vehicle range from a given battery pack capacity**



SiC MOSFET

Inverter-level Loss Comparison: 650V Rated Silicon vs. Silicon Carbide

(same voltage and switching frequency)



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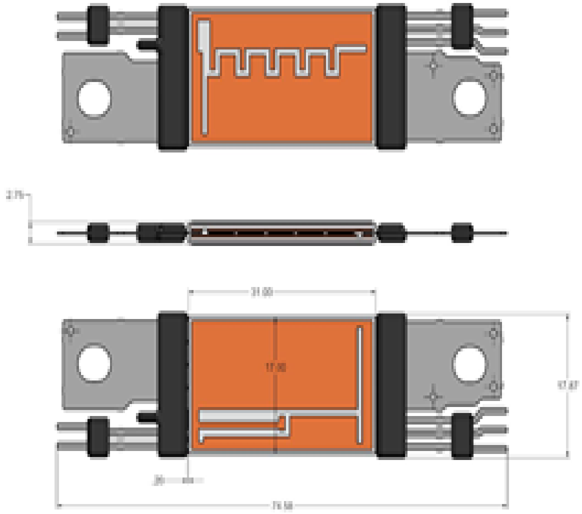
Technical Accomplishments
1200V SiC devices

- 5 dies in parallel
- NTC thermistor in substrate



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Technical Accomplishments
Viper 4 1200V Switching Data

- Turn off behavior at 835V, 672 A
- 1.1kV peak voltage
- ~ 29 mJ E_{off} (25°C)

Technical Accomplishments
Viper 4 1200V Switching Behavior

- Turn On at 835V DC
- 744 A peak current
- ~ 75 mJ E_{on} (25°C)

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Technical Accomplishments
Viper 4 1200V Body Diode Switching

- Body Diode Reverse Recovery Energy
- 835V, 672A
- ~ 14 uJ (25°C)

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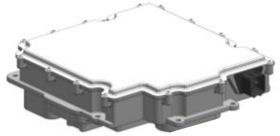
Technical Accomplishments
Viper 4 1200V SiC and IGBT Inverter Test Data (Losses)

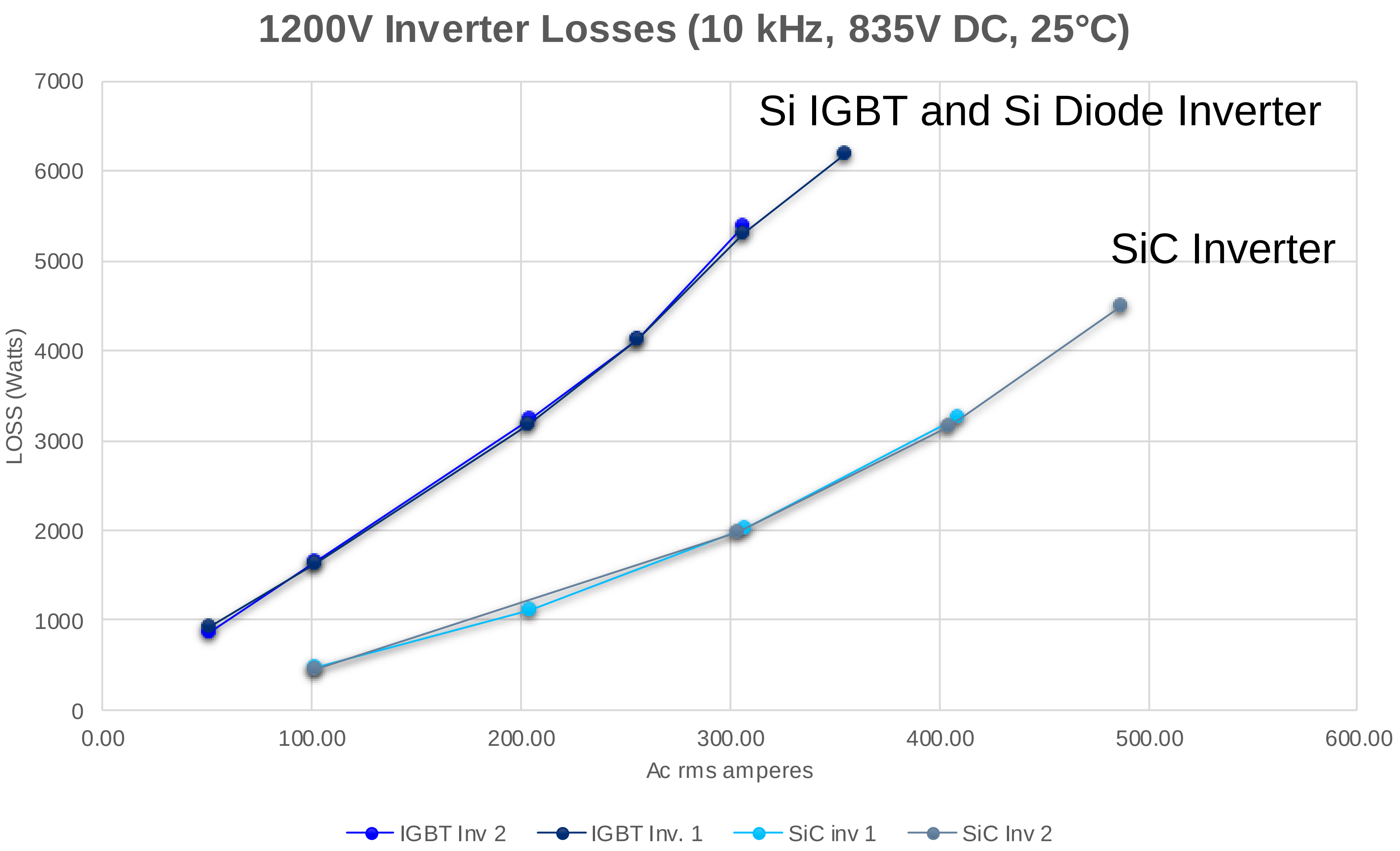


Viper 2: Si IGBT and Diode

- Built in Temperature Sense Diode

Viper 4: SiC MOSFET

- Thermistor on substrate for temperature estimation



Collaboration

Volvo

- Inverter system requirements

Delphi Technologies, Mr. Monty B. Hayes, PI

- Semiconductor device floorplan
- Power semiconductor design, build and characterization
- Inverter design, build and characterization
- Device and power module pre-qualification testing

Wolfspeed, Dr. Jeffrey Casady, PI

- 650V & 1200V SiC MOSFET design and layout
- Fabrication and characterization of the SiC MOSFET
- Pre-qualification testing at the die level

Oak Ridge National Laboratory, Ms. Laura Marlino, PI

- Support with packaging

Response to Previous Years Comments

- The reviewer observed a target for bus voltages lower than 650V, and noted a 650V single switch device with double sided cooling and a half-bridge inverter. The reviewer asked if there is significant price differential among the 1,200V, 900V and 650V SiC devices.
    - *Price is based on the area of the device more so than the voltage rating. If the same current is required at each voltage level there will be a higher cost for the higher breakdown devices due to the lower efficiency MOSFET components.*
- The reviewer remarked that packaging the SiC device is an important step, but is just one of many elements needed to see incorporation of the technology. The reviewer is sure Delphi understands this comment and the need for more extensive work to move this technology into a vehicle.
    - *The key is to package the devices into an inverter (or DC/DC Converter or Charger) to get the learning of the operation at the system and vehicle level.*
- The reviewer noted that Wolfspeed, ORNL, and Volvo are the partners and their roles are listed. It is not clear what the roles of Volvo are.
    - *Volvo helped to provide inverter requirements.*
- The reviewer said the major concern is the completion rate after about 1.5 years since the project started. Some of the objectives, such as the current rating of a single switch, have not been met in the design and fabrication. The reviewer noted that some of the remaining barriers are significant, especially with the amount of project time left. Among those are the cost-effectiveness and the final prototype fabrication, test and modification (if need be).
    - *We were a little behind on the initial activity but have caught up and completed the program.*

Remaining Challenges and Barriers

- For this program completion there are no remaining challenges or barriers
- In general going forward for future products we need to optimize the performance of the system to maximum the efficiency/performance versus the cost of the system
- Continue to drive down cost for the SiC components

Future Work

- Continue to develop lower loss power semiconductor devices
- Continue to develop better thermal stacks
- Continue to optimize the performance of the system components
- Continue to drive down cost for SiC power semiconductors
- Continue to develop supporting system components to optimize SiC benefits

Summary

- Developed a 650V and 1200V, 175°C junction Temperature SiC MOSFET devices for Traction Drive Inverter Applications
- Targeting 7-8mW R_{DSON} for 650V rated devices, 175°C junction temperature rated
- Targeting 10-12mW R_{DSON} for 1200V rated devices, 175°C junction temperature
- Top side solderable and sinterable
- R_g optimized for Traction Drive Inverter applications
- Devices were assembled without wirebonds per switch in dual-side cooled power modules
- Characterized for performance (DC and dynamic) over temperature range, and found to be consistent up to 750A
- For reliability, initial measurements of power cycling (ΔTJ=100˚C, 36,000 cycles, no failures) and short-circuit (8μs) were both very encouraging

Summary (Continued)

- Built a 650V breakdown voltage SiC prototype inverter and compared the losses and performance to a best in class Si IGBT and Diode based inverter
- Built a 1200V breakdown voltage SiC prototype inverter an compared the losses to best in class Si IGBT and Diode based inverter
- The electrical characteristics should allow up to 80% conduction loss reduction in the inverters during normal drive cycles.
- Targeting these SiC based inverters for 2021MY introduction

Summary

	2020	2025	Achieved 650V	Achieved 1200V
Cost ($/kW)	<3.3	<2.7		
Specific Power (kW/kg)	>14.1		52	65
Power Density (kW/L)	>13.4	>100	45	58

- WBG device power and voltage levels and availability
- WBG multi-physics integration designs to enable optimal use
- High temperature and isolation materials

Acknowledgments

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Thank you.

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